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Research Article

Hail netting changes to spray droplets and patterns in grape canopies

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Abstract

While hail netting in vineyards provides effective protection to wine grapes (*Vitis vinifera* L.) from hail, pests, and bird damage, it may also affect the spray efficacy. This study tested the interaction between hail netting and location within the canopy in determining spray droplet characteristics. Two grape cultivars (Petite Sirah FPS 04 and Touriga Nacional FPS 05) grafted onto 1103P rootstock were examined to assess spray coverage, droplet size distribution, and deposition within grapevine canopies under netted and unnetted conditions. Spray droplets were measured using spray cards placed at five locations within the canopy. Significant interactions were observed primarily at the base of the canopy directly above the cordon, where grape clusters are most concentrated. Unnetted Touriga Nacional exhibited higher spray coverage compared to Petite Sirah, attributed to its looser cluster structure. Hail netting standardized all parameters across both cultivars, mitigating the influence of canopy and cluster differences. Hail netting created smaller, uniformly distributed droplets within the canopy, an essential characteristic of effective pest and disease control. Conversely, without netting, larger droplets were unevenly distributed, predominantly settling on the outer and lower canopy sections. Hail netting also maintained deposit densities within recommended ranges, supporting effective pest and disease management without compromising spray coverage. The consistent spray coverage achieved with hail netting across all canopy locations highlights its role in improving application uniformity and grapevine health, leading to evenly ripened, high-quality fruit. Contrary to the perceived

risk of reducing spray efficacy, hail netting appears to enhance vineyard spraying outcomes, potentially offsetting netting costs.

Keywords

canopy, coverage, deposit density, droplets, grapes, hail netting

Introduction

Wine grape (*Vitis vinifera* L.) is a highly-value crop in Texas. The state's wine and grape industry contributes approximately $20 billion to the economy (National Association of American Wineries 2022). Wine grape production spans a wide range of climates across Texas, resulting in diverse grape varieties with unique flavors and characteristics (Basinger and Hellman 2007, Townsend and Hellman 2014). Like other major crops grown in semi-arid areas, grape production particularly in the Texas High Plains American Viticulture Area faces various biotic and abiotic stresses such as pests and extreme weather conditions (Basinger and Hellman 2007, Graff et al. 2022). The challenges posed by these factors necessitate the adoption of protective measures in viticulture such as the use of hail netting designed to protect grapevines from a range of risks.

The use of hail netting in viticulture has emerged as an important practice in managing grape canopies and influencing overall grape quality (Pagay et al. 2013, Ruland et al. 2023). It has gained popularity as a protective measure against various environmental stressors including adverse weather conditions (hail, excessive sunlight) and bird damage. In addition to its protective function, hail netting has been shown to have an impact on the microclimate within the grape canopy, influencing factors like temperature, humidity, and light exposure (Manja and Aoun 2019, McCaskill et al. 2016). Research conducted by Ruland et al. (2023) suggested that hail netting modified vine physiology by reducing air and leaf temperatures and the light infiltration into the canopy. The reduction in canopy air temperatures, leaf temperature, and light infiltration tend to increase the severity of disease such as downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysiphe necator*) (Keller 2015).

While hail netting is effective in protecting grapes from external factors, it may also have some positive or negative implications in relation to spray applications. Spray management in grape production allows vineyard managers to efficiently and precisely address pest and disease challenges, ensuring the health and quality of grape crops (Warneke et al. 2022). Through the strategic use of sprays, growers can optimize pest control, mitigate fungal infections caused by downy mildew, black rot (*Guignardia bidwellii*), and powdery mildew, and enhance overall grape yield and quality (Gisi 2002, Hoffman and Wilcox 2002, Perria et al. 2022, Romanazzi et al. 2016). This approach not only contributes to sustainable farming practices but also promotes the production of premium grapes, resulting in wines of superior taste and character.

One of the main challenges in vineyard spraying is achieving thorough spray coverage (Campos et al. 2019). Vineyards are typically comprised of closely planted vines and densely packed vegetation, which often poses potential issues including inability to penetrate densely shaded areas, resulting in inconsistent application of agrochemicals (Balsari et al. 2008, Gil et al. 2014). The typical hail netting used by grape growers in Texas is made of black plastic mesh with cell dimensions of 4.0 mm by 6.0 mm. The hail netting is fastened to the sides of a vertically shoot-positioned canopy, enclosing it between the two sides of the netting. This confined canopy could be more difficult for spray droplets to penetrate. In addition, grape canopy characteristics, such as size, shape, and orientation of leaves, also affect how well the agrochemical droplets adhere and spread on the leaf surface (Rosell and Sanz 2012, Walklate and Cross 2012).

The use of hail netting likely alters droplet characteristics and spray distribution, impacting pesticide efficacy. Currently, no standardized metrics link spray coverage and deposit density to insect or disease control. This highlights a significant gap in viticulture research and practice. Effective pest and disease management in vineyards relies heavily on precise application of pesticides and fungicides (Pertot et al. 2017). Therefore, it is important to assess how hail netting management interacts with spray application and canopy features, considering its implications for spraying efficacy, to fully optimize its advantages for the intended purpose in the vineyard. In this study, we hypothesize that hail netting in vineyards influences spray distribution within the canopy of grape cultivars with different canopy architecture, affecting the uniformity and effectiveness of material applications. The specific objectives of this study are the following:

1. Assess how the canopy characteristic variation affects spray uniformity and retention with and without hail netting.
2. Determine how hail netting alters droplet size distribution and spray coverage uniformity within grapevine canopies.
3. Determine the impact of hail netting on spray deposit density and coverage quality on grapevine canopies.

Materials and Methods

Experiment design and management

Field experiment was conducted in 2023 at the research vineyard in the Department of Plant and Soil Science at Texas Tech University, Lubbock, TX (33°35'10.824"N, 101°47'2.904"W). The vineyard soil is a deep, well-drained Amarillo series fine sandy loam and a deep well drained Estacado series clay loam with slopes of 0 to 1% (United States Department of Agriculture 2023). The vineyard was planted in 2017 with vine by row spacing of 1.5 m by 3.0 m with a north-south orientation. Vines were bilateral cordon-trained (cordons established on a cordon wire 1.0 m above the soil surface). The experimental design was a randomized complete block with two established grape cultivars (*Vitis vinifera* L. Petite Sirah FPS 04 and *Vitis vinifera* L. Touriga Nacional FPS 05) grafted onto 1103P rootstock, two hail netting treatments (netted and unnetted), and

four replicates. For each treatment, one vine was randomly selected from the ten vines in each replicate. Five rectangular pieces of water-sensitive paper (WSP), each measuring 26 mm × 76 mm (Syngenta Crop Protection AG) and with holes, were securely attached to the trellis structure at various locations on the canopy using zip ties, as shown in Fig. 1. The spray experiment was conducted on September 23, 2023, when the canopy and the clusters were at their maximum, and the average relative humidity was 57%. Relative humidity levels above 80% can impact the effectiveness of WSPs. The vineyard and WSPs were sprayed with water using venturi airblast sprayer (Model 45, Cima) calibrated to 374 L ha^{-1}, operated at 140 kPA pressure, and traveling at a speed of 4.8 km h^{-1}. After application, the WSPs were collected and stored individually in Ziplock bags to prevent any contact between samples.

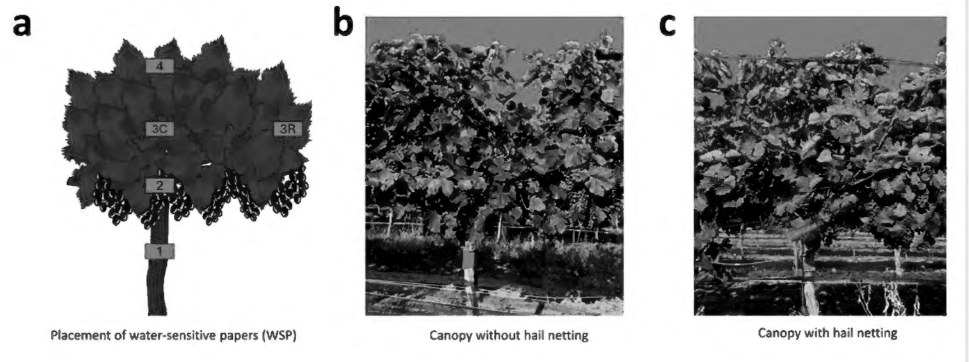

Figure 1. doi

Images showing the (a) location of the water-sensitive papers (WSP) on the canopy. C means center and R means Right, and the grape canopies (b) without hail netting and (c) with hail netting located in the Department of Plant and Soil Science - Texas Tech University research vineyard in Lubbock, TX.

Data collection and analysis

Each WSP was scanned at 600 dpi in gray scale using an Epson V550 flatbed photo scanner. The scanned area was cropped to take out areas where holes were punched for attaching the WSPs onto the canopy. The images were then analyzed using DepositScan, a portable scanning system for spray deposit qualification developed by the United States Department of Agriculture-ARS Application Technology Research Unit in Ohio, USA, following the procedure described by Zhu et al. (2011). For this study, relevant data that were obtained from the software included DV_1 (μm), DV_5 (μm), spray coverage (%), and deposit density (number of droplets cm^{-2}). DV_1 indicates that 10% of the spray volume is in droplets smaller than the specified size and may contain a major part of the fine driftable droplets. DV_5 indicates that half of the spray volume is in droplets larger than the specified size and half is smaller. Spray coverage refers to the percentage of the selected area covered by the spray, representing a measure of spraying efficiency in vineyards. Deposit density refers to the amount of spray deposits that adhered to the surface per unit area.

Spray parameters were analyzed using the GLIMMIX procedure for a generalized linear mixed model in SAS 9.4 (SAS Institute 2013). Hail netting treatment (with or without), cultivars, and canopy locations were treated as fixed effects and replicate was treated as a random effect (Littell et al. 2006). Treatment interactions were tested to determine whether to pool information by fixed effect factor. A probability level of .05 was used for all the analysis.

Results and Discussion

Interaction between hail netting management and grape cluster characteristics

Significant interactions between hail netting and cultivar treatments were observed for all parameters at Location 2 only (Fig. 2). As a result, DV_1, DV_5, spray coverage, and deposit density on Location 2 were analyzed separately by hail netting and by cultivar treatment and the results are shown in Table 1. Location 2 is an area in the canopy where most grape clusters can be found (Fig. 1). Without hail netting, Touriga Nacional had significantly higher DV_1, DV_5, and spray coverage on Location 2 of the canopy compared to Petite Sirah (Table 1). When netted, there were no significant differences in DV_1, DV_5, spray coverage, and deposit density on Location 2 between the two cultivars (Table 1).

Table 1.

Comparison of spray parameters on Location 2 of the canopy between Petite Sirah and Touriga Nacional grape cultivars at the research vineyard in the Department of Plant and Soil Science at Texas Tech University, Lubbock, TX in 2023.

Parameter	Treatment	Cultivars		
		Petite Sirah	Touriga Nacional	*Diff* ‡
DV_1	Netted	572 a†	394 a	*178 ns*
	Unnetted	247 b	534 a	*287 **
DV_5	Netted	776 a	960 a	*819 ns*
	Unnetted	882 a	1628 a	*746 **
Coverage	Netted	41 a	32 b	*9 ns*
	Unnetted	32 a	64 a	*32 ***
Deposit density	Netted	205 a	455 a	*250 ns*
	Unnetted	428 a	179 a	*249 ns*

†For each parameter and cultivar, netting treatment means with the same letter are not significantly different at the 0.05 probability level.

‡For each parameter and netting treatment, Diff refers to the difference between cultivars. ns means not significant. * and ** indicate significance at the .05 and .01 probability levels, respectively.

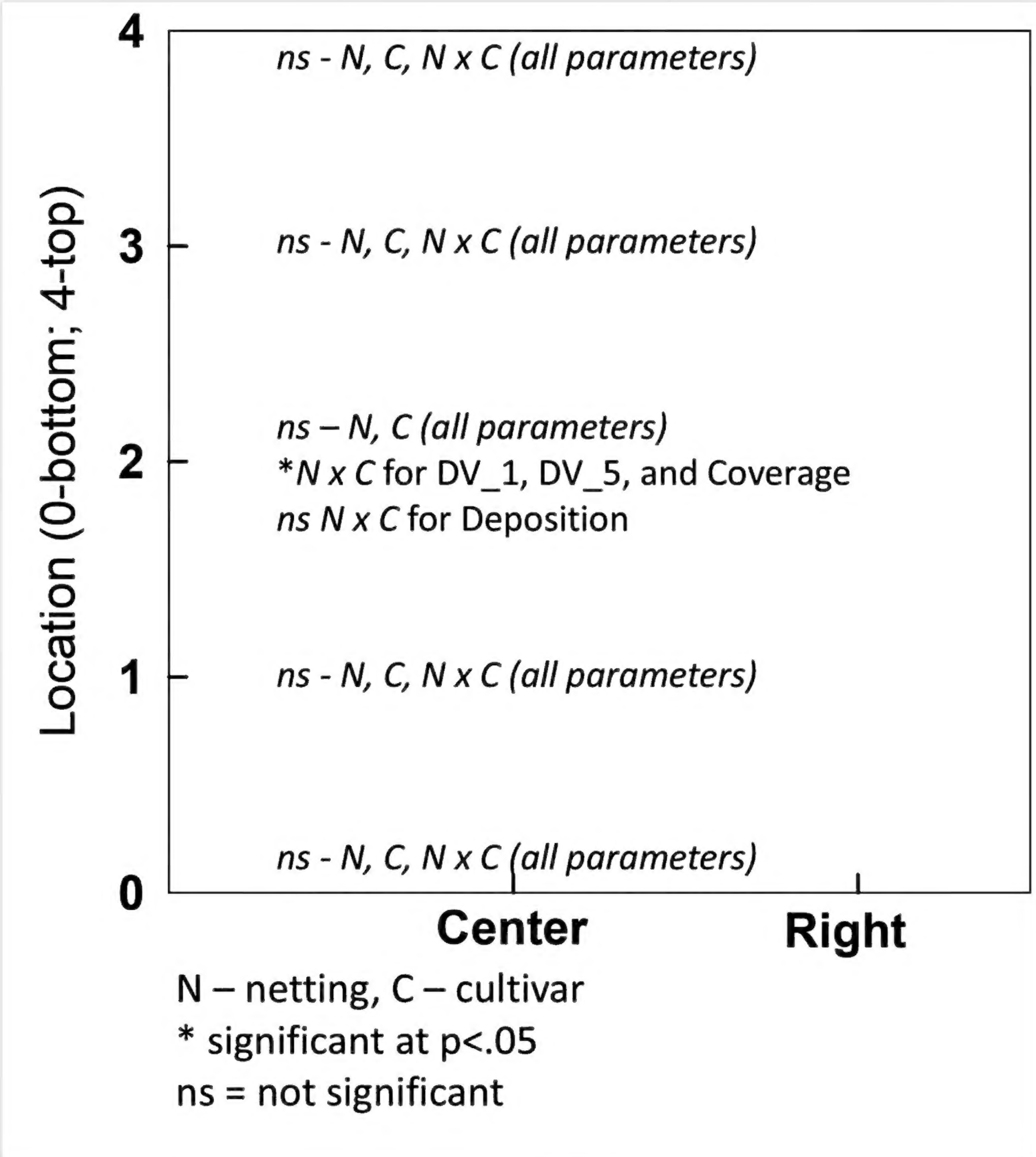

Figure 2. doi

Test of fixed effects and interactions between hail netting and cultivar treatments per location on the canopy.

Without hail netting, the observed difference in the spray parameters between cultivars on Location 2 can be attributed to the difference in the canopy and grape cluster characteristics between Petite Sirah and Touriga Nacional. The canopy of Petite Sirah (also called Durif) vines tends to be moderately dense. The leaves are medium-sized, and the vine generally has a vigorous growth habit (Morsil et al. 1992). The foliage can provide good shade to the grape clusters, protecting them from excessive sun exposure. Petite Sirah clusters are typically medium in size, compact, often winged, and have short to medium peduncles that results in berries that are tightly packed. The canopy of Touriga Nacional vines can vary, but generally, it has moderate to dense foliage (Castro et al. 2005). The leaves are often small to medium in size, and the vine tends to have a more restrained growth habit compared to some other varieties. Touriga Nacional grape clusters are generally small to medium in size and the berry clusters have a loose density (Hoffman and Wilcox 2002). The higher DV_1, DV_5, and spray coverage values of

Touriga Nacional compared to Petite Sirah without hail netting suggest that the loosely packed berry clusters on Touriga Nacional at Location 2 allowed for better adherence and penetration of the spray droplets. On the other hand, the implementation of hail netting eliminated the influence of the canopy and grape cluster characteristics on the distribution and penetration of spray materials. Hail netting created a more uniform barrier over the canopy and grape clusters, which helped standardize the spray distribution on Location 2. The hail netting potentially reduced the variability caused by canopy and grape structure by providing a consistent layer that impacted how spray materials are deposited. Variability in spray coverage can result in uneven pest and disease pressure (Gossen et al. 2008), impacting the quality and yield of the grape harvest. By creating a more uniform application environment, hail netting helps reduce this variability. Consistent coverage ensures that the active ingredients are evenly distributed, leading to more reliable pest and disease suppression. This can also translate into better economic outcomes, as the effectiveness of each spray application is maximized.

Influence of hail netting on droplet size

For both cultivars, results showed that hail netting produced smaller droplets that were more uniformly distributed across all locations on the canopy (Fig. 3). Without hail netting, the distribution of smaller droplets was uneven, with the majority of the smaller droplets concentrated at the top portion of the canopy for both cultivars (Fig. 3). Hail nets are typically made of mesh with small openings. When larger droplets of spray material pass through these openings, several physical phenomena may come into play. The mesh acts as a physical barrier that disrupts larger droplets, breaking them into smaller ones. This disruption occurs due to the mesh's fine structure, which forces the larger droplets to split upon impact with the net's fibers, resulting in a more uniform distribution of smaller droplets beneath the netting. Surface tension also causes the liquid to deform and separate when interacting with the net's surface. As larger droplets come into contact with the mesh, surface tension forces them to break apart into smaller droplets to pass through the small openings of the netting.

Based on the patterns of DV_5 on the Petite Sirah canopy, larger droplets were greater on the outer side of the canopy regardless of the hail netting treatment (Fig. 4). For Touriga Nacional, larger droplets were distributed more to the lower portion of the canopy and less to the outer side portion when hail netting was installed (Fig. 4). Similar to the patterns observed for DV_1, the results for DV_5 indicated that larger droplets were unevenly distributed within the canopy in the absence of hail netting. Specifically, larger droplets tended to settle more on the lower and outer sides of the canopy for both cultivars (Fig. 4).

Research supports the notion that smaller droplets enhance the effectiveness of sprays applications. For example, studies have shown that droplet size affects the deposition and retention of pesticides on plant surfaces. Smaller droplets tend to adhere better and provide more uniform coverage, leading to improved pest and disease control (Ebert and Downer 2006, Post and Roten 2018, Stevens et al. 1993). Smaller droplets have a higher

likelihood of adhering to plant surfaces due to their larger surface area to volume ratio (Massinon et al. 2017, Spillman 1984). Smaller droplets can also penetrate dense grape canopies more effectively, reaching areas that larger droplets might struggle to access. The increased adhesion to the plant surface improves the efficacy of the application because of reduced loss of applied substance to the environment. In addition, the uniformly dispersed droplets under netted conditions ensure that the entire target area receives the necessary coverage without gaps, which is crucial for effective control of pests and pathogens.

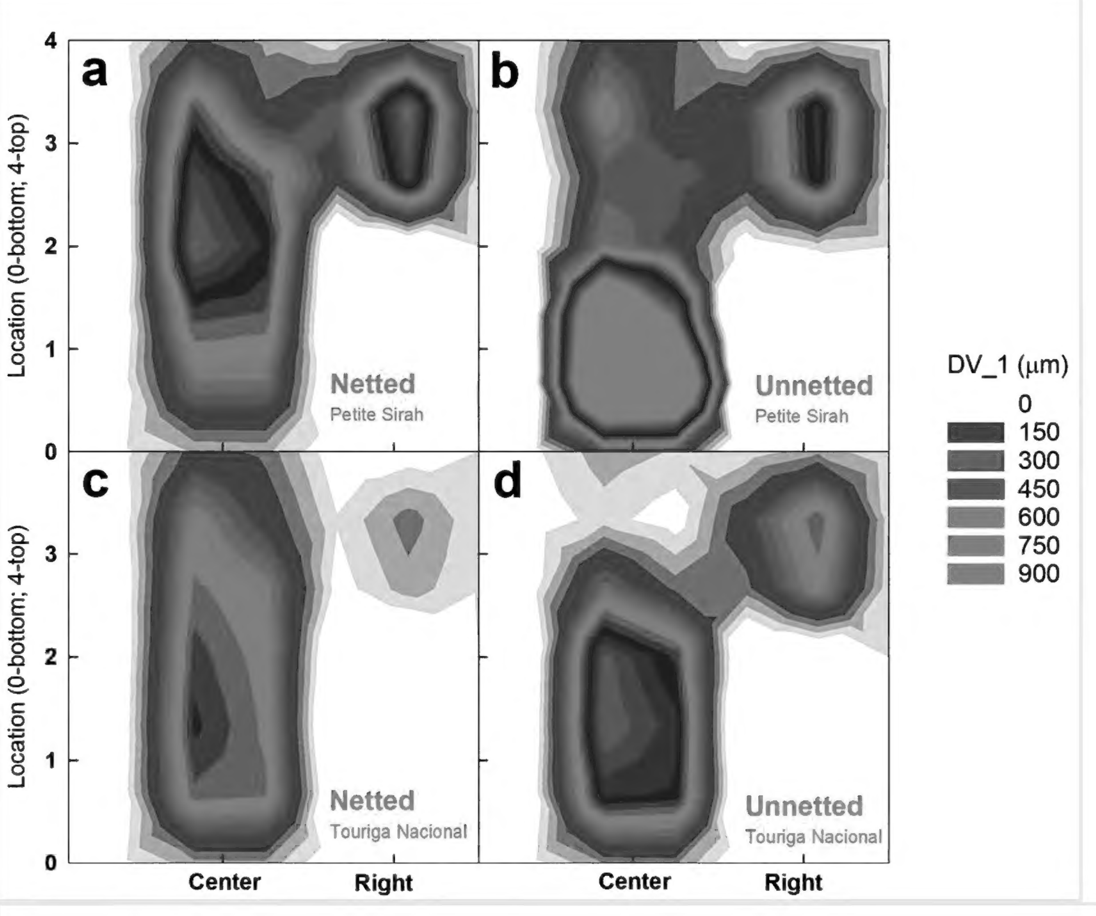

Figure 3. doi

Variations in DV_1 across different levels in the canopy of two grape cultivars (Petite Sirah and Touriga Nacional) grown under netted and unnetted conditions at the research vineyard in the Department of Plant and Soil Science at Texas Tech University, Lubbock, TX in 2023.

Influence of hail netting on spray coverage and deposit density

Among treatments, Petite Sirah with hail netting produced a consistent spray coverage across different locations on the canopy (Fig. 5). Without hail netting, higher spray coverage was observed on the outer side and bottom part of the canopy of Petite Sirah (Fig. 5). The spray coverage on Touriga Nacional was inconsistent throughout the canopy regardless of the netting treatment (Fig. 5). Even distribution of sprayed material impacts the efficacy of pest and disease control, as well as the overall health and productivity of the grapevines. Uneven spray coverage can leave grape clusters and foliage vulnerable to pests and diseases (Austin et al. 2011, Oberti et al. 2016). Pests and diseases that escape control in certain areas can weaken the vines, reduce photosynthetic activity, and impact the vine's ability to produce and ripen fruit (Palliotti et al. 2014, Thiéry et al. 2018). Uneven spray coverage on grape clusters may also result in inconsistent ripening,

affecting the uniformity of grape quality, leading to variations in sugar levels, acidity, and flavor within the same vineyard (Ozdemir et al. 2017, Wise et al. 2010). Consistent and thorough spray coverage is crucial for producing high-quality, evenly ripened fruit.

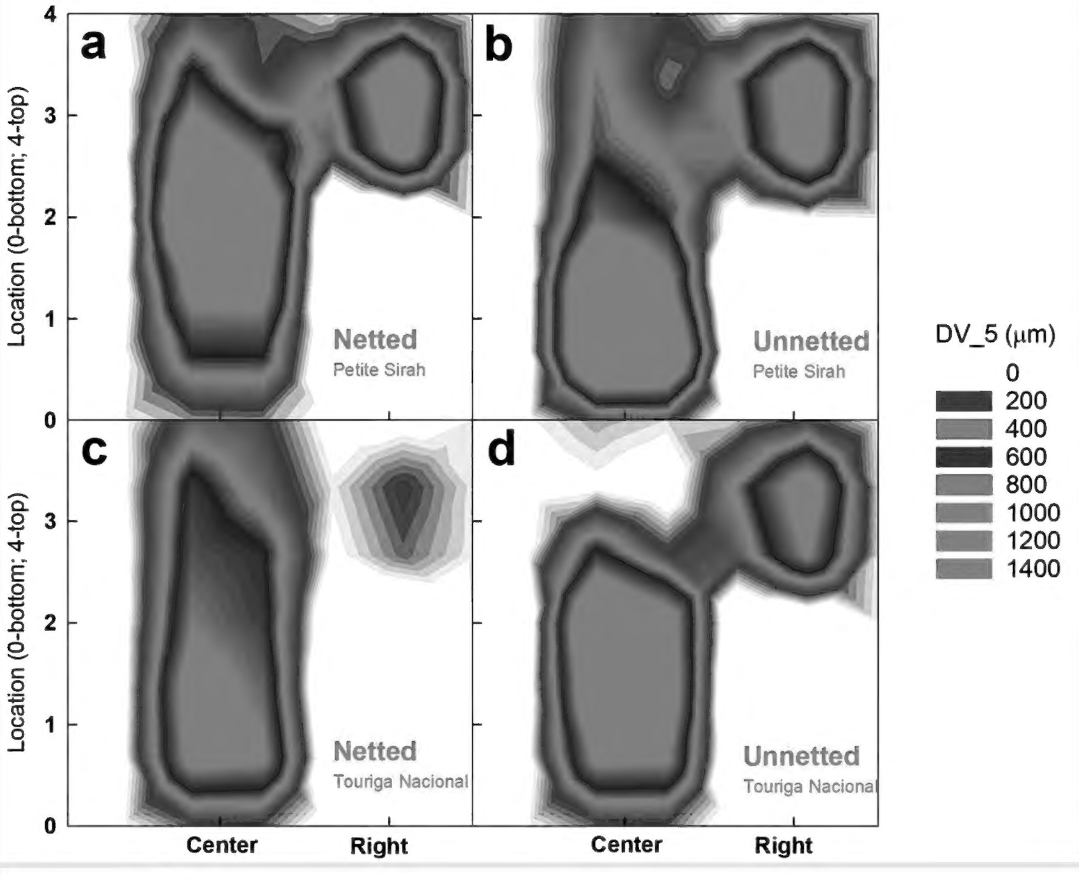

Figure 4. doi

Variations in DV_5 across different levels in the canopy of two grape cultivars (Petite Sirah and Touriga Nacional) grown under netted and unnetted conditions grown at the research vineyard in the Department of Plant and Soil Science at Texas Tech University, Lubbock, TX in 2023.

Based on the deposit density pattern across all locations as shown in Fig. 6, hail netting resulted in a more even and uniform distribution of particles across the target surface for both cultivars. In contrast, without hail netting, deposit density was higher in both the upper and lower sections of the canopy, while the middle portion exhibited a lower density (Fig. 6). This result highlights the potential of hail netting as a tool for improving spray deposition efficiency due to the observed uniformity of the spray across the application area when hail netting is implemented. Uniform distribution helps in achieving consistent results across the target area. The number of deposits per cm² can impact the efficacy of the treatment. Too few deposits may result in inadequate control of pests or diseases, while too many may lead to wastage of the solution and potential damage to the plants or environment. Results shown in Fig. 6 are consistent with the results for the spray coverage when hail netting is implemented as previously shown in Fig. 5. Adequate coverage is necessary to ensure that plant canopy receives an even distribution of materials, and that pests or pathogens are effectively controlled.

Currently, there are no standardized metrics that relate the combination of spray coverage and deposit density to insect or disease control, posing a significant challenge

in optimizing pesticide application. Syngenta Crop Protection AG has suggested thresholds of 20-30 droplets per cm² for insecticides and 50-70 droplets per cm² for fungicides (Warneke et al. 2022), providing useful guidelines for achieving effective pest and disease management. Results of this study indicated that hail netting did not adversely affect spray coverage, ensuring that the deposit density remained within the recommended ranges. This finding emphasizes the adequacy of current spray techniques in maintaining effective coverage for insect and disease treatments, even when protective netting is employed.

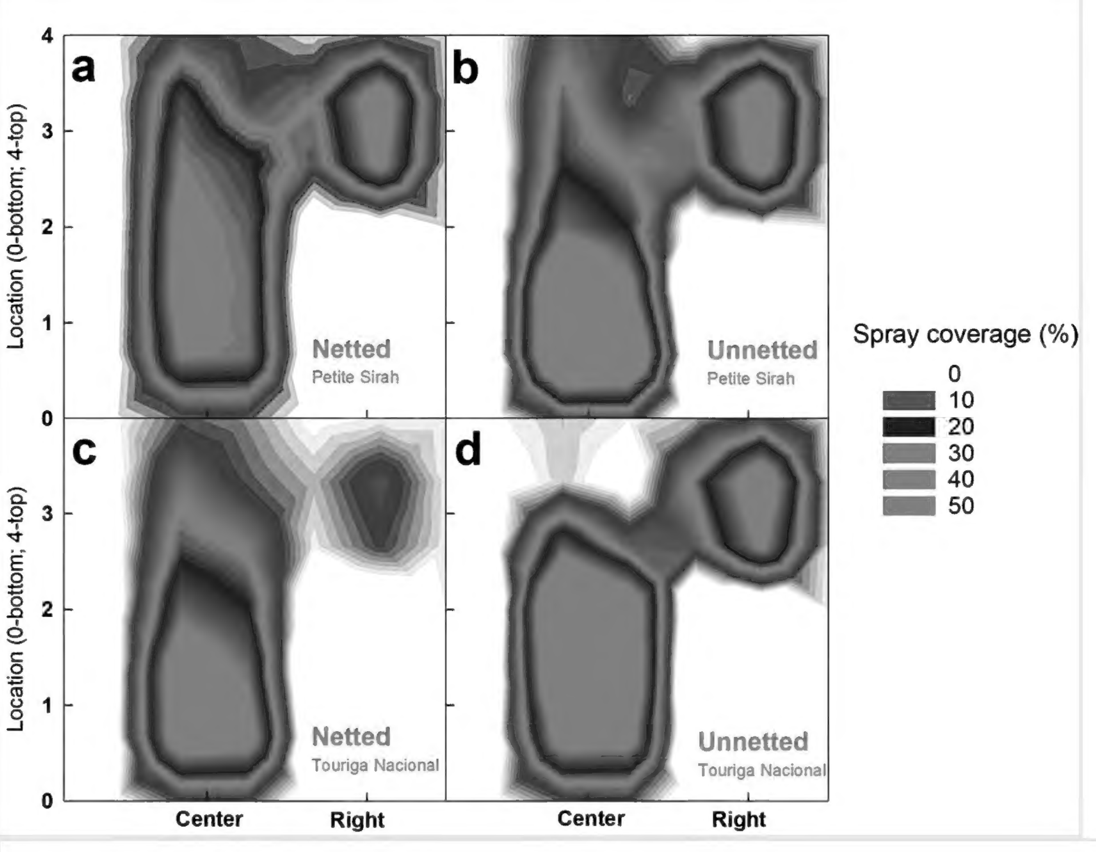

Figure 5. doi

Variations in the spray coverage across different levels in the canopy of two grape cultivars (Petite Sirah and Touriga Nacional) grown under netted and unnetted conditions grown at the research vineyard in the Department of Plant and Soil Science at Texas Tech University, Lubbock, TX in 2023.

Conclusions

This study elucidated the significant interactions between hail netting management and grape canopy and cluster characteristics, particularly in relation to spray coverage, droplet size distribution, and deposition on grape canopies. The findings highlighted that hail netting notably impacts these parameters, with distinct variations observed between cultivars and canopy locations. At Location 2, where grape clusters were most abundant, the unnetted Touriga Nacional exhibited higher DV_1, DV_5, and spray coverage compared to Petite Sirah, attributed to its looser cluster structure. However, hail netting standardized the spray distribution across both cultivars, mitigating the influence of inherent canopy and cluster characteristics. Hail netting produced smaller, uniformly distributed droplets across the canopy, enhancing spray effectiveness. This uniformity in

droplet size and distribution ensured consistent coverage and deposition, crucial for effective pest and disease control. Without netting, larger droplets tended to concentrate unevenly, particularly on the outer and lower parts of the canopy, highlighting the benefit of netting in achieving more uniform application. The consistent spray coverage achieved with hail netting across various canopy locations, as observed in both spray coverage and deposition analyses, emphasizes the role of netting in improving application uniformity. This uniformity is essential for maintaining grapevine health, ensuring even ripening of grape clusters, and achieving high-quality fruit production. Moreover, the hail netting maintained deposit densities within recommended ranges, affirming its efficacy in supporting effective pest and disease management without compromising spray coverage. Overall, hail netting not only provides physical protection to grape canopy and clusters but also enhances the efficiency of spray applications, leading to improved pest and disease suppression and potentially better economic outcomes. These findings suggest that integrating hail netting in vineyard management practices can significantly contribute to the consistency and quality of grape production. Future research should encompass different growth stages, environmental conditions, and pest behaviors to ensure broad applicability. Additionally, studies should investigate the retention of spray materials in the hail nets and the integration of advanced spray technologies and precision agriculture techniques to enhance the accuracy and efficiency of pesticide applications.

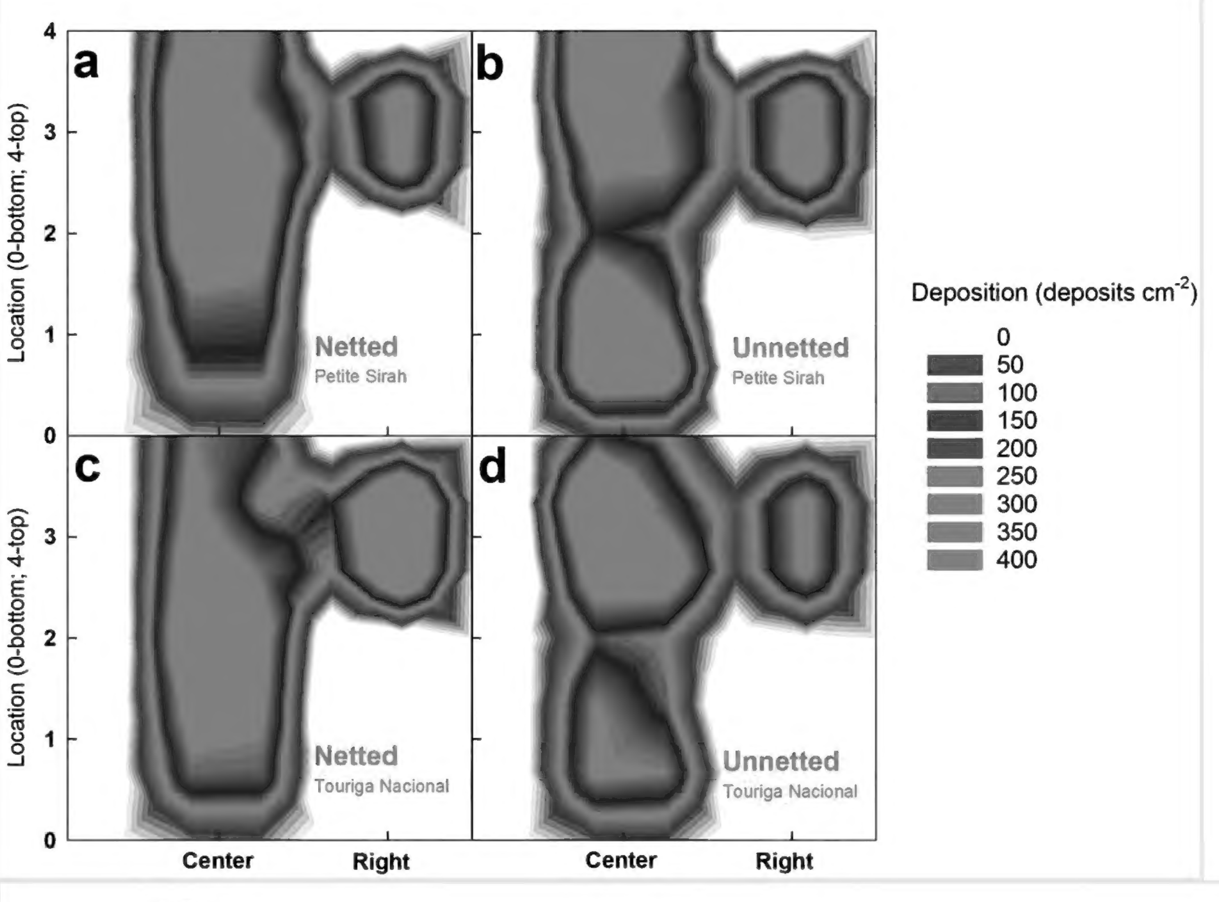

Figure 6. doi

Variations in spray deposit density across different levels in the canopy of two grape cultivars (Petite Sirah and Touriga Nacional) grown under netted and unnetted conditions grown at the research vineyard in the Department of Plant and Soil Science at Texas Tech University, Lubbock, TX in 2023.

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Conflicts of interest

The authors have declared that no competing interests exist.

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